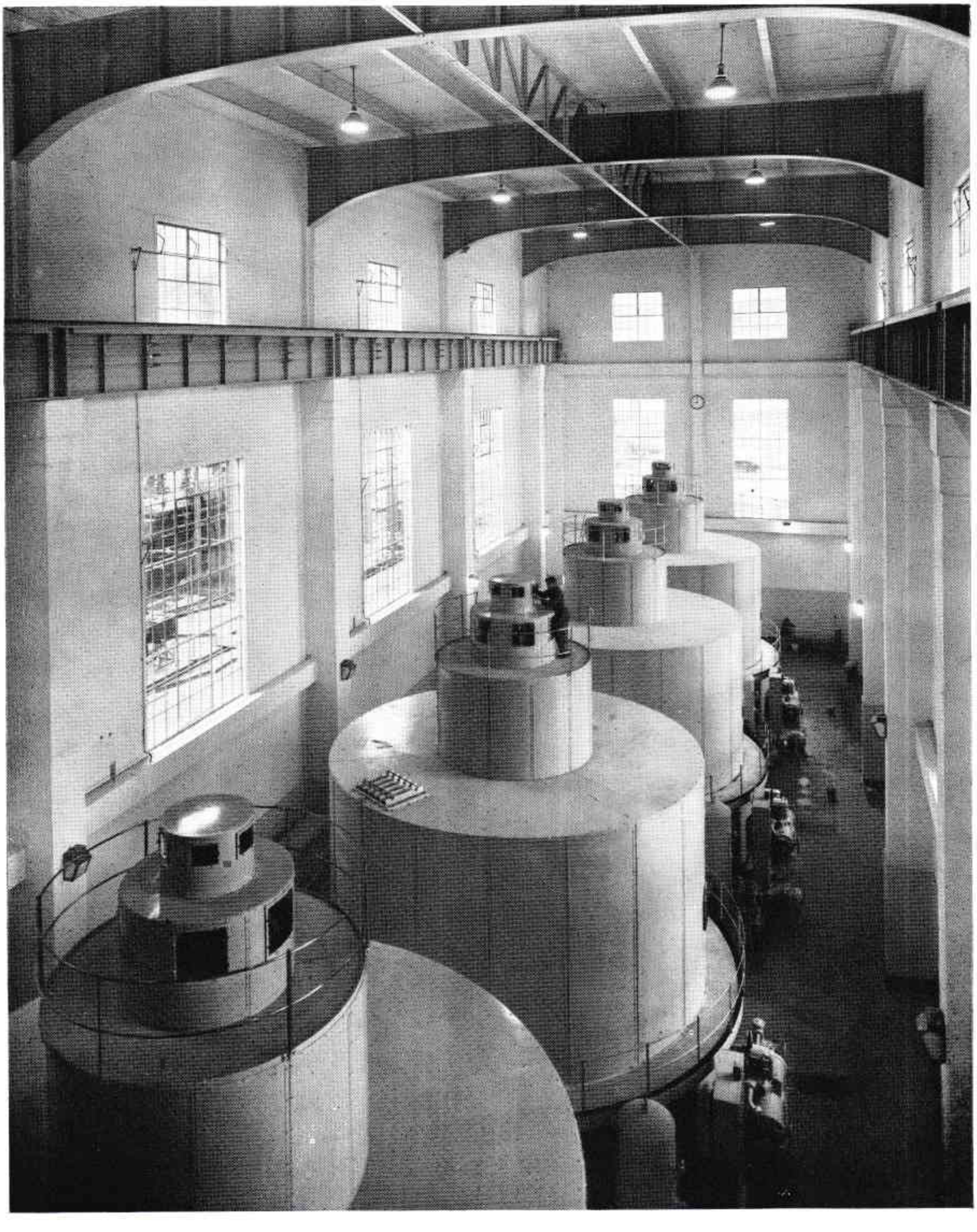
LOCH SLOY
POWER SCHEME

of the

NORTH OF SCOTLAND
HYDRO-ELECTRIC BOARD

'ENGLISH ELECTRIC'



The four 45,500 *h.p. water turbine generating sets in Loch Sloy power station of the North of Scotland Hydro-Electric Board*

Loch Sloy Power Scheme
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North of Scotland Hydro-Electric Board

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THE CHOICE OF Loch Sloy as a source of water supply for the largest hydro-electric station in the British Isles was based on three factors which are fundamental for the production of hydro-electric power in large quantities :—

(i) The rainfall in the area is very heavy.
(ii) The physical layout is exceptionally favourable.
(iii) There is a centre demanding heavy peak electrical load near-by.

It was estimated that the long-term average rainfall over the catchment area would be 115 inches per year, but over the past three years the actual amounts recorded by individual gauges have been as follows :—

Year.	Total Rainfall.
1948	163 inches.
1949	154 „
1950	138 „

When the full catchment area is in use, every inch of rain will give about 1,000,000 units, and therefore the extra rainfall will result in substantial additional financial gain without any additional capital expenditure.

Loch Sloy itself was quite small having a natural length of under 1 mile and a width of only a few hundred yards ; also its catchment area was only 6½ square miles. However, its location only 2 miles from Loch Lomond and 760 ft above its level gives the water there great potential value, and there was a suitable site for the power station on the banks of Loch Lomond at a convenient point. In addition, the steep sided valley in which Loch Sloy lies and the rock formation at the river outlet from the loch gave good conditions for building a high dam.

Heavy rainfall and a satisfactory physical layout are not sufficient to justify building a generating station if the power cannot be used effectively, but Loch Sloy is only 40 miles from Glasgow with its heavy industrial load and short-time peak power demands.

PREVIOUS SCHEMES

The advantages of the site were first considered in 1906 and various proposals have been investigated since then, the major efforts before the present development being in 1936 and 1937.

The 1937 scheme involved over 200,000 kW of plant in 5 or 6 sets of 45 or 40 MW each, which is considerably larger than the scheme finally adopted. These sets would have been horizontal and some of them would have been arranged with a pump connected to the alternator shaft at the opposite end to the turbine. These pumps were to be of 20,000 or 25,000 kW capacity and would have been driven by the alternators working as synchronous motors, to raise water from Loch Lomond back to Loch Sloy during times of low load on the system. The water would then have been returned through the turbines during peak periods to augment the power from Loch Sloy's catchment area. With this arrangement a greater installed plant capacity was economical although the net number of units generated would be no greater.

An earlier scheme was even larger and would have had an eventual capacity of 360,000 kW with 100,000 kW of pumps, but these schemes did not proceed due to opposition from other interests even though the cost per kW was lower than for a comparable steam station.

The two fixed terminal towers and the control point were situated on the left bank of the loch and the two towers on the right bank were movable, which permitted the material to be dumped where required on the dam. The skips each contained 4 cubic yards of material weighing about 7 tons, and the average amount of concrete placed per day was 800 tons.

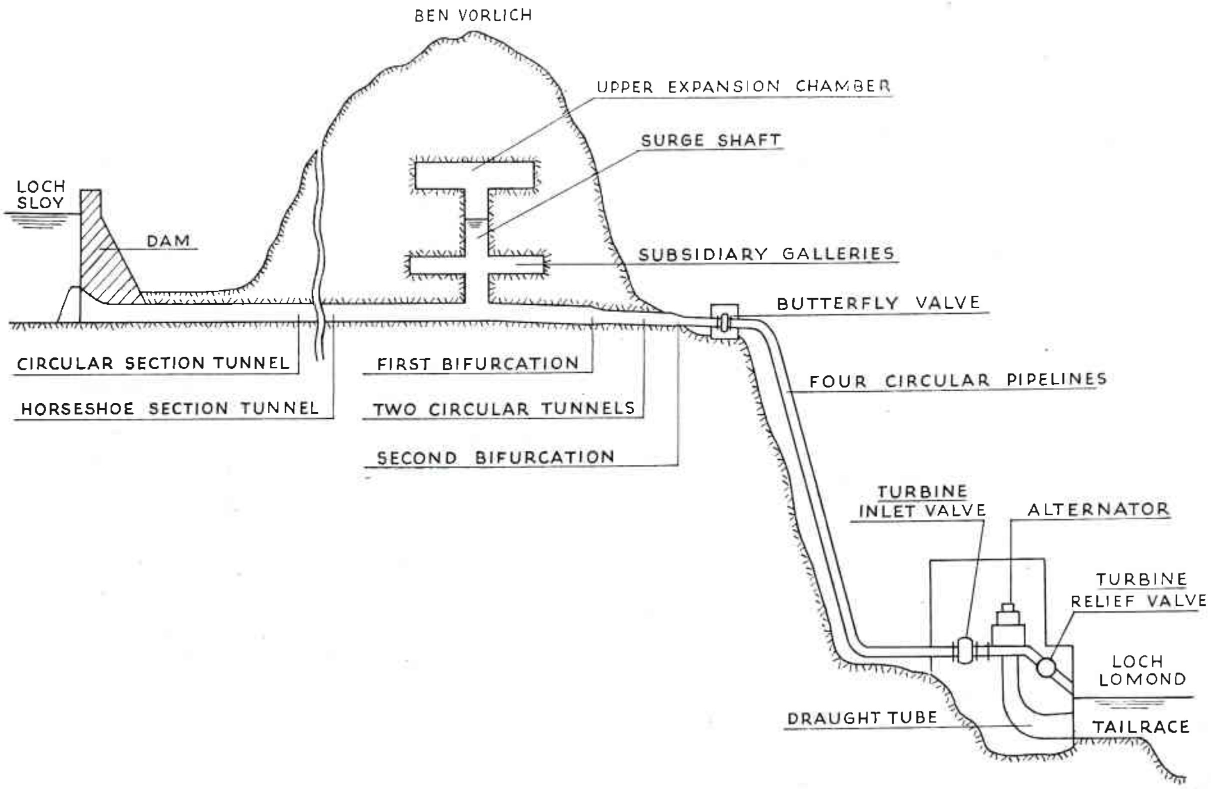
Because of the contraction which takes place when concrete sets, the dam was built in sections, each buttress forming a separate section, and the upstream part of each buttress was constructed several lifts in advance of the stem. The gap between the sections (Fig. 2) was 6 ft wide, and these gaps were closed at least three months after placing the concrete in the buttresses.

Water from the loch passed through a temporary opening in the dam until the work was sufficiently far advanced, when the gap was closed by a timber stop gate on the upstream side and the space was then permanently plugged, after which filling of the reservoir proceeded.

Screens and Gates

The flow of water to the tunnel from the reservoir is through the base of the intake tower situated in the dam, as seen in Fig. 1. A fixed coarse screen with 6 in. spacing between bars, and a movable fine screen with 3 in. spacing, are located at the intake, and behind the screens is the emergency guard gate. This gate consists of a number of 16¼ in. diameter horizontal steel rollers with small brass tubes between each on the upstream side, so arranged that the water pressure forces them into the spaces between the large rollers, making the gate reasonably water tight. The gate is arranged so that it can close automatically under gravity at a speed of 20 ft/min. in an emergency, but opening is by a hoist located at the top of the intake chamber. It can also be used when it is necessary to de-water the main gate chamber which is immediately downstream of it, for maintenance of the main control gate. This main gate is of the counterbalanced type and is normally under water at all times.

Fig 3. Diagrammatic section, showing dam, pipelines and power house. (*Not to Scale*)



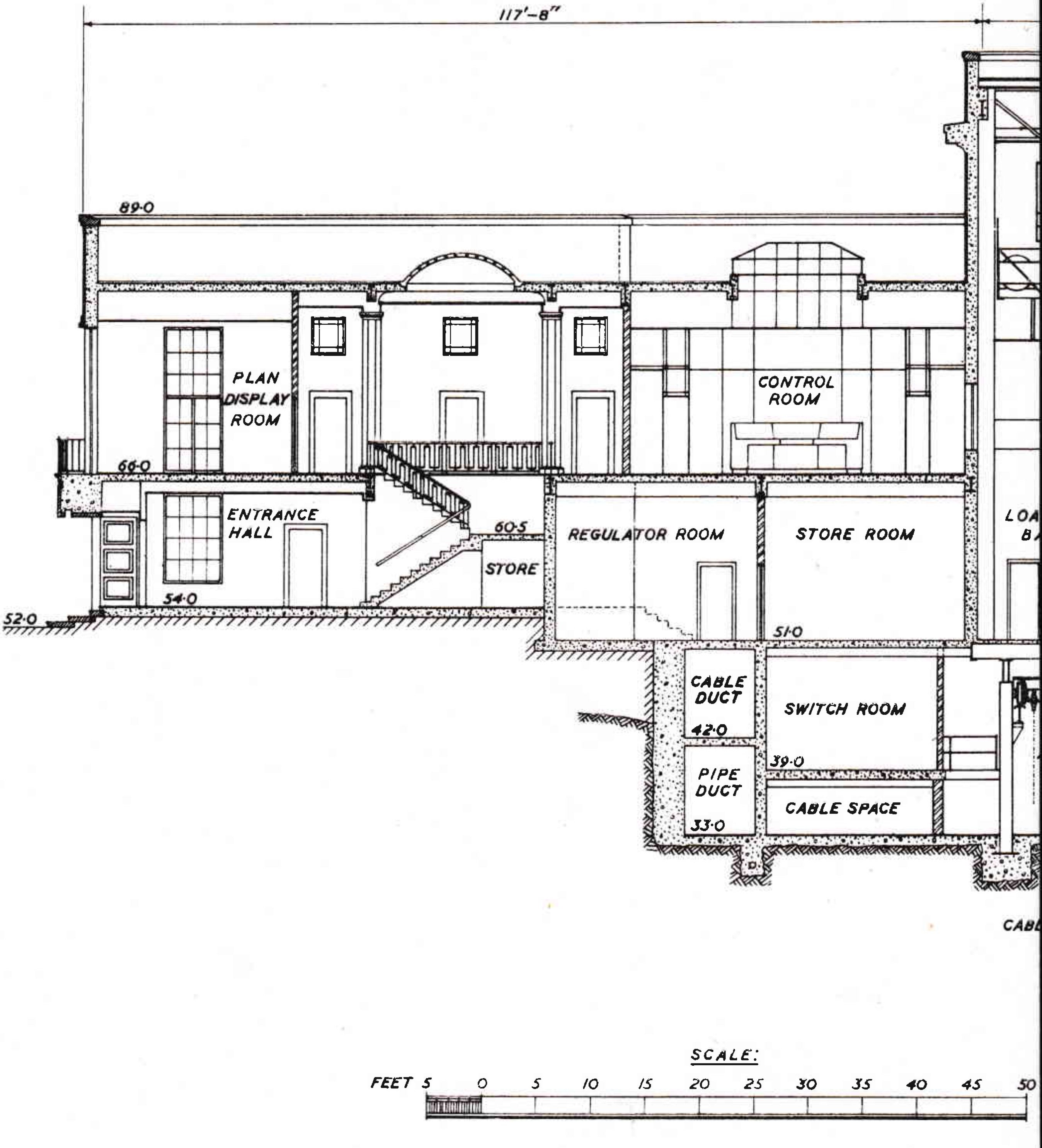
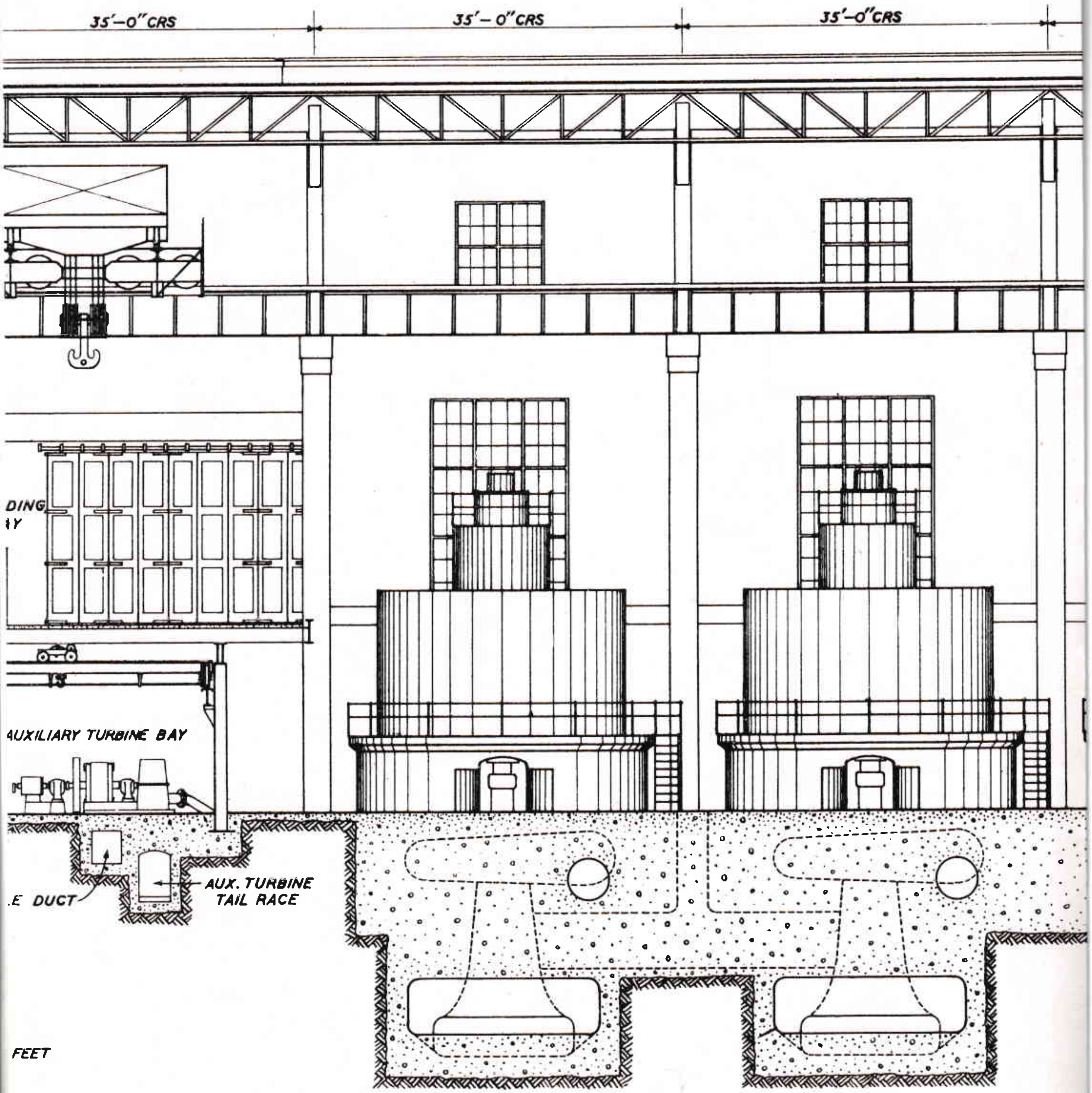
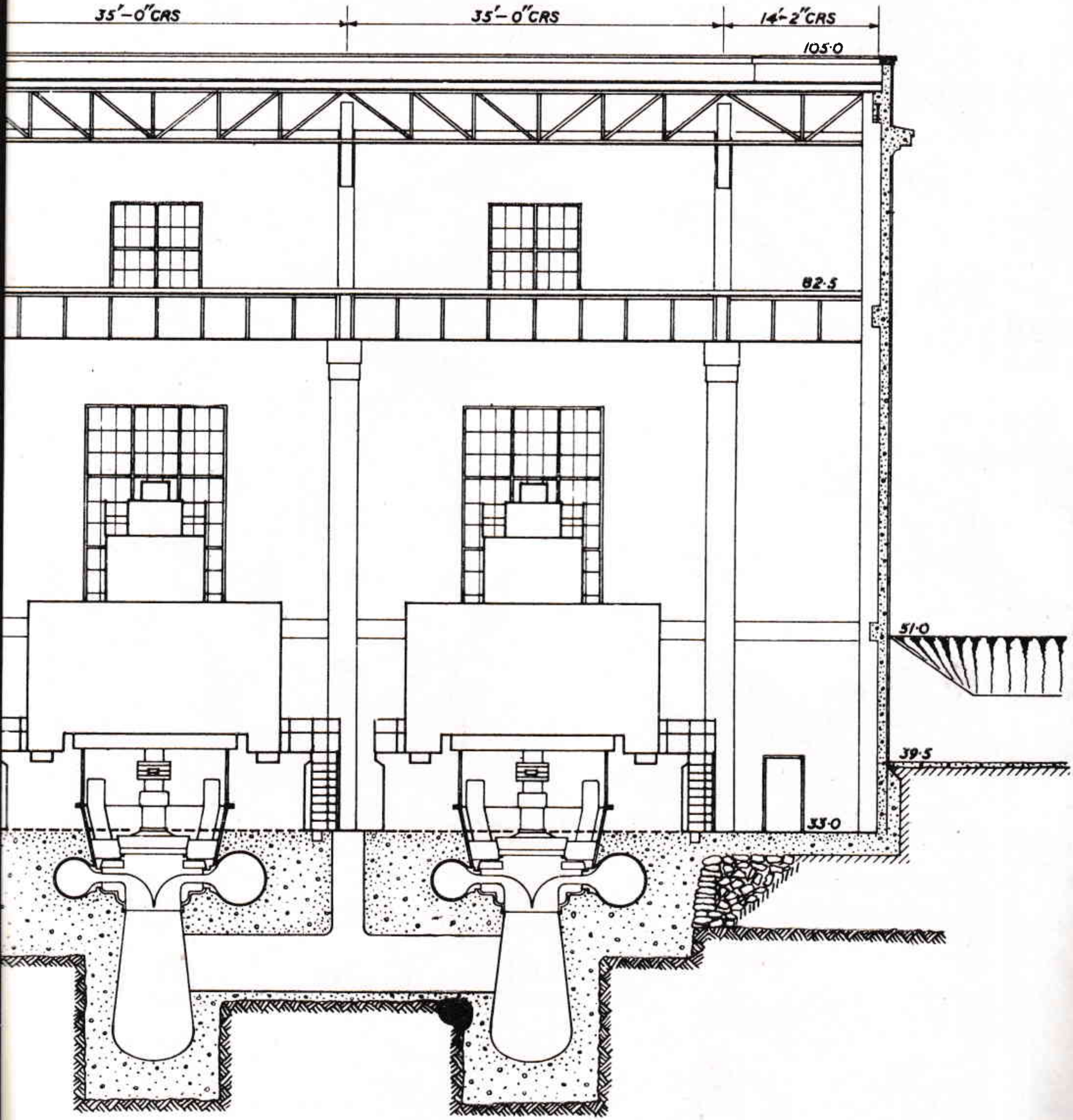

117'–8"
89·0
PLAN DISPLAY ROOM
CONTROL ROOM
66·0
ENTRANCE HALL
60·5
REGULATOR ROOM
STORE ROOM
LOA
BA
STORE
54·0
52·0
51·0
CABLE DUCT
42·0
SWITCH ROOM
39·0
PIPE DUCT
33·0
CABLE SPACE
CABL
SCALE:
FEET 5 0 5 10 15 20 25 30 35 40 45 50

PLATE I **General arrangement of the power house**

(By courtesy of Messrs. James Williamson and Partners, Civil Consulting Engineers)




35'–0" CRS
35'–0" CRS
14'–2" CRS
105·0
82·5
51·0
39·5
33·0

Tunnels

Fig. 3 shows a diagrammatic section of the dam, tunnels, pipelines and power house.

From the intake there is a short length of circular steel-lined tunnel 13 ft 6 in. diameter and 750 ft long, with a double bend to connect with the line of the main tunnel which is driven through Ben Vorlich.

The main portion of the tunnel is concrete lined, 8,200 ft long ($1\frac{1}{2}$ miles) and of inverted horseshoe section with an equivalent diameter of approximately 16 ft. The tunnel was driven through rock (mica schist) by blasting, and the spoil was removed by diesel and electric locomotives hauling trucks along a temporary narrow gauge track. The main work was carried out from three faces, one at the downstream end from the point where the tunnel emerges on the banks of Loch Lomond, and two in opposite directions from an extra adit driven some distance from the dam at right angles to the main tunnel. A fourth face was also used for a short length of tunnel adjacent to the dam.

The average rate of progress in the tunnel was about 64 ft per week and the maximum reached was 103 ft. During tunnelling, a severe fault was met and a diversion of the tunnel had to be made. The concrete lining was reinforced where necessary, and in parts where loose rock was encountered the reinforcing was made up of steel joists which were left embedded in the lining.

Surge Shaft

About 1,000 ft from the outlet of the tunnel there is a vertical surge shaft, 26 ft diameter and 200 ft high, cut in the rock. This shaft is to control and stabilise pressure surges which occur when the load on the generating sets varies. When load is thrown off, the water supply to the turbines is reduced, which causes a rise in level in the surge shaft. To cover the extreme case of full load being thrown off all four sets, as would occur if the switchgear bus-zone protection tripped in both zones, an expansion chamber 38 ft by 90 ft is provided at the top of the surge shaft. This is to avoid any danger of spilling. A small subsidiary stream is brought into this chamber by means of a branch tunnel.

To cater for load being suddenly thrown on the sets (e.g., when two sets are on light load with minimum water level in the shaft), in which case the level in the surge shaft will go down due to acceleration of the water, and to avoid any possibility of air being drawn in, two subsidiary horizontal galleries are connected to the surge shaft a short distance above the point where it enters the main tunnel. Each gallery is of approximately the same size as the main tunnel (16 ft equivalent diameter) and 120 ft long.

Valve House

Five hundred feet beyond the surge shaft, the horseshoe tunnel divides into the two circular steel lined tunnels each about 500 ft long and 10 ft diameter. These each divide into two 7 ft steel pipes immediately they emerge from the hillside, making four pipes in all which are encased in concrete. Shortly after the two bifurcations there is a 7 ft diameter hydraulically operated butterfly valve in each pipe. These valves are normally operated locally when required but usually they are left open.

To open a valve it is first necessary to balance the water pressure on both sides, and to accomplish this a 10 in. diameter by-pass is provided, with a hand-operated sluice valve through which the pipeline can be gradually filled. When the pipeline is full and the pressure on both sides of the valve is equal, the main butterfly valve is opened by an oil operated servo-motor controlled by solenoids, and the by-pass is then closed.

Closing of the valve can be effected by a push button in the valve house which operates the solenoid controlling the oil servo-motor. In an emergency the valve can also be closed by push button from the power station control room, or if the pipeline fails causing excessive flow a mechanical paddle will close the valve.

Oil pressure for operation is obtained from A.C. motor-driven pumps and is stored in an air/oil pressure receiver in the valve house.

Pipelines and Power House

The four pipelines from the valve house to the power house on the banks of Loch Lomond are 7 ft diameter at the top, tapering in stages to

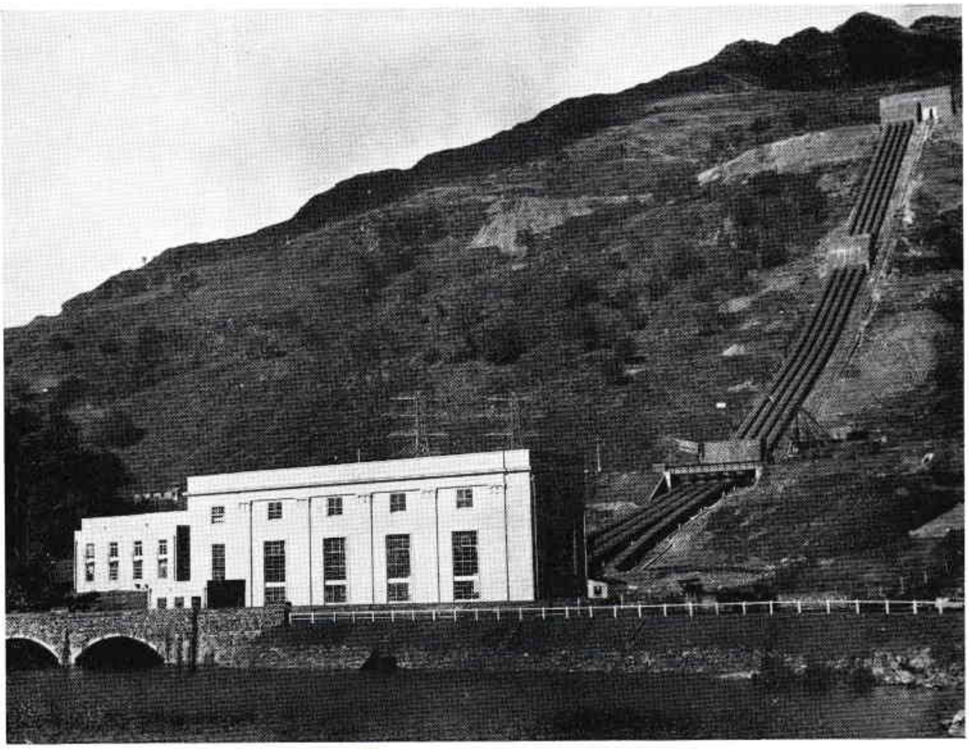


Fig. 4. Loch Sloy power station, with pipelines and valve house

6 ft 4 in. at the power house where the thickness of the pipeline is $1\frac{9}{16}$ in. The total length of each pipeline is 1,500 ft and it was assembled at site from 24 ft lengths welded and tested at the works. The site joints were all riveted.

Four anchor blocks are provided ; one can be seen in Fig. 4 built into the valve house wall, two are on the hillside, and the last is behind the power house and this also forms the foundations for the transformers. At the upstream end of each pipeline before each anchor block there is an expansion joint to allow for temperature changes.

Turbine Inlet Valves

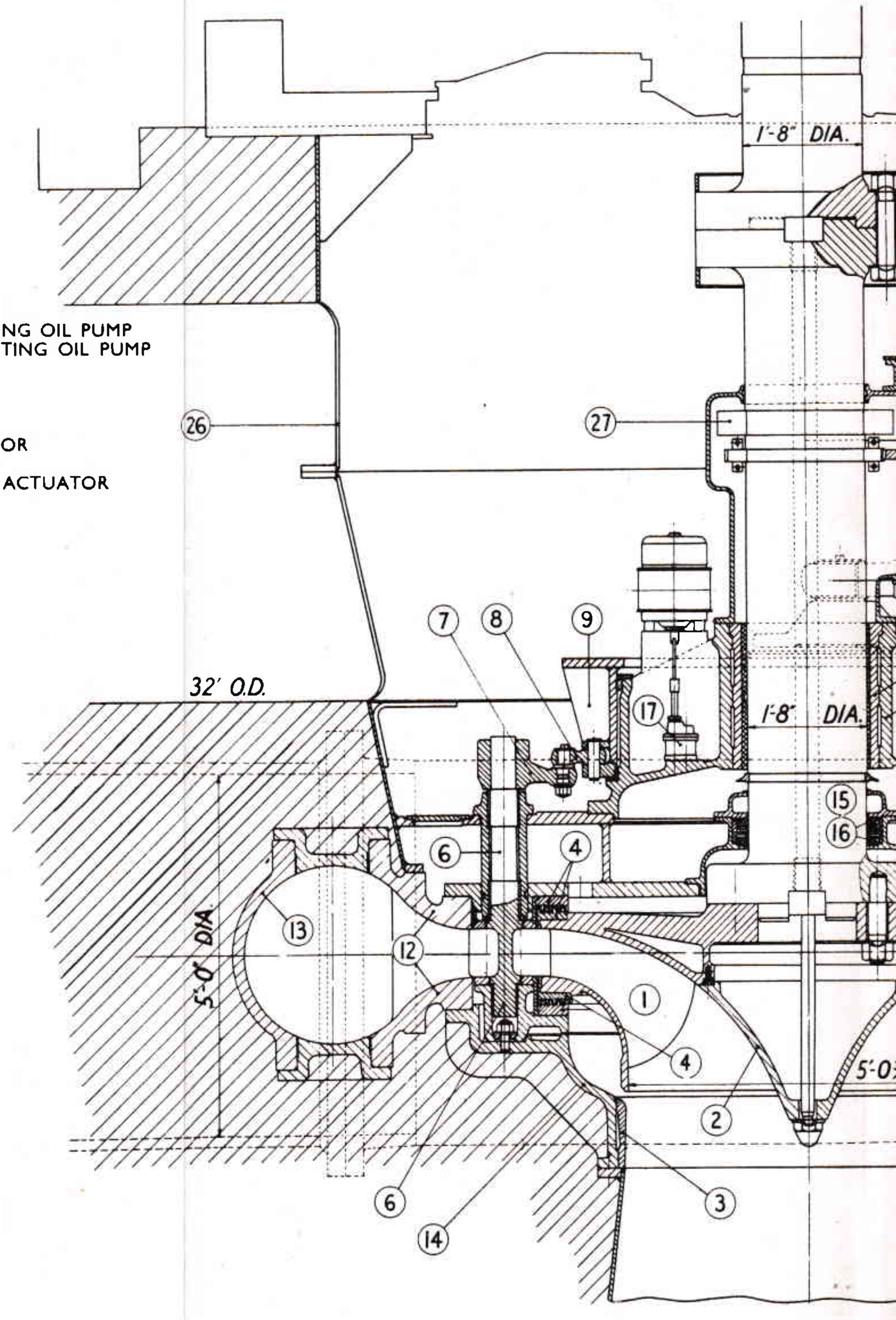
Each pipeline is connected to the turbine through a 6 ft 4 in. diameter 'English Electric' cylindrical balanced valve which is a type much used in hydro-electric stations for a number of years. The maximum static water head on the valve is 920 ft, equivalent to a pressure of approximately 400 lb/sq. in. and the valve is designed to operate against this full unbalanced pressure when priming the spiral casing. Unlike the pipeline valves no by-pass is fitted. The valve also has to close against full flow if necessary.

The closing member of the valve consists of a cylinder which seals against an inner body inside the valve and fixed to the outer body by ribs. The upstream nose of the inner body and some of the ribs can be seen in Fig. 5. The closing force on the cylinder is obtained from pipeline water pressure on the back end of the cylinder, admitted through a control valve. To guard against too rapid closure at the end of the stroke, which would set up excessive water hammer, a control screw which travels with the valve cylinder reduces the supply of water and so progressively diminishes the speed of closing. Opening of the valve is effected by releasing the water pressure on the closing side of the cylinder which is then opened by the pipeline pressure. The control valve is operated by a lever for manual opening of the valve, but closing can be carried out electrically in an emergency.

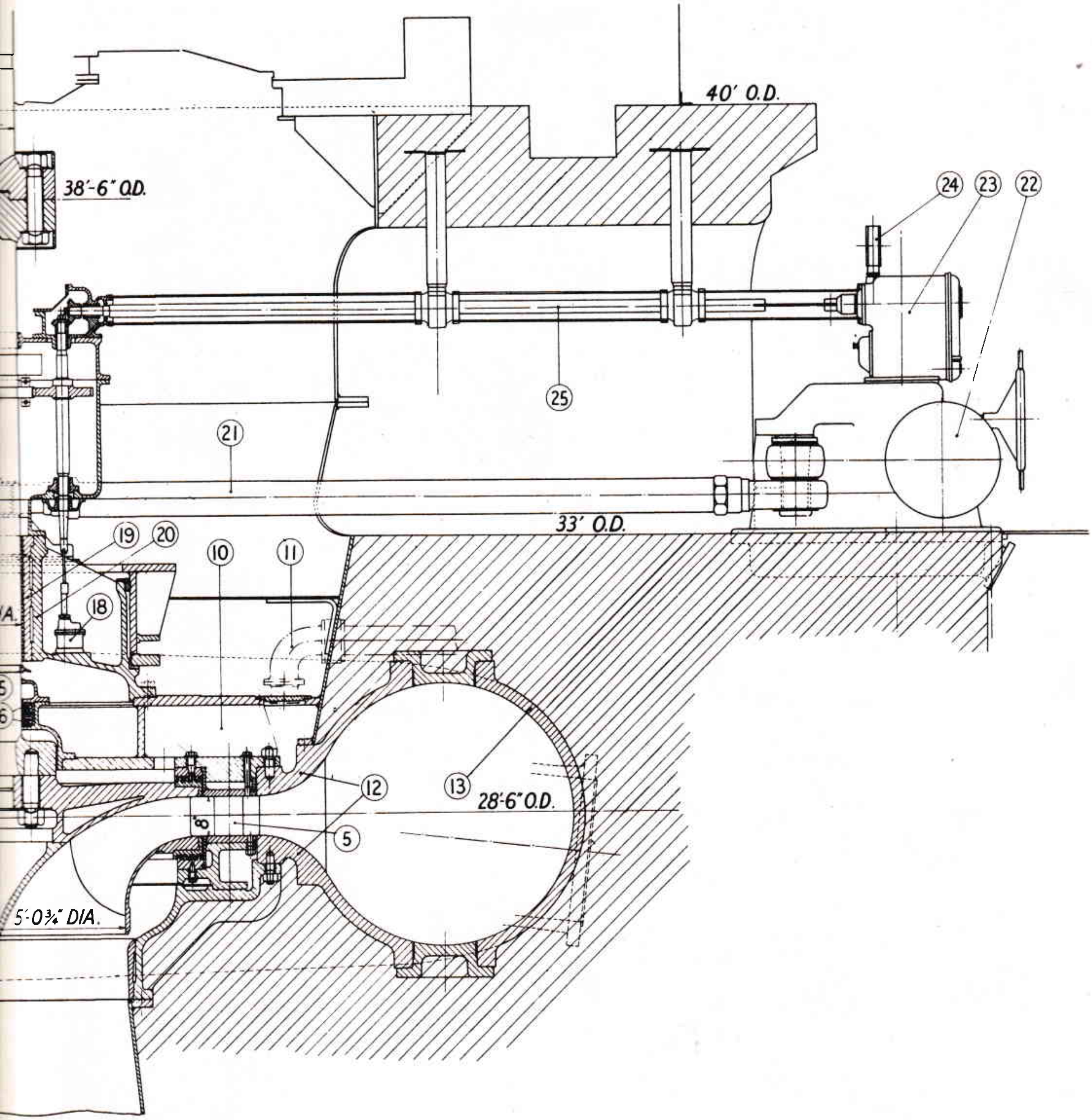
The connection of the upstream flange of the valve to the downstream flange of the pipeline

PLATE II **Sectional elevation of 45,5**

Ref. No.	Description
1	STAINLESS STEEL RUNNER
2	RUNNER COVER
3	STAINLESS STEEL THROAT RING
4	SEALING RINGS
5	GUIDE VANES
6	GUIDE VANE TRUNNIONS
7	REGULATING LEVERS
8	BREAKING LINKS
9	REGULATING RING
10	TOP COVER
11	BALANCING PIPES
12	SPEED RING
13	CAST STEEL SPIRAL CASING
14	FOUNDATION RING
15	TURBINE SHAFT
16	SHAFT GLAND CARBON RINGS
17	ELECTRICALLY DRIVEN LUBRICATING OIL PUMP
18	MECHANICALLY DRIVEN LUBRICATING OIL PUMP
19	TURBINE BEARING
20	TURBINE BEARING HOUSING
21	MAIN REGULATING RODS
22	OIL PRESSURE SERVO-MOTOR
23	AUTOMATIC GOVERNOR ACTUATOR
24	GOVERNOR TACHOMETER
25	DRIVING SHAFT FOR GOVERNOR ACTUATOR
26	GENERATOR SUPPORT
27	OVERSPEED PENDULUM



45,500 h.p. water turbine at Loch Sloy



introduced a difficult problem as under the high head and with the large diameter any flexible coupling was not considered to be satisfactory. Closing of the final joint was actually carried out in the following manner. The downstream flange of the pipeline was left undrilled and 2 in. short of the calculated position of the mating flange of the valve. The valve was positioned, the gap accurately measured and a ring then made to these dimensions. Meanwhile the pipeline flange was drilled through the bolt holes in the valve flange. Finally the ring was dropped in position and bolted up.

Turbines

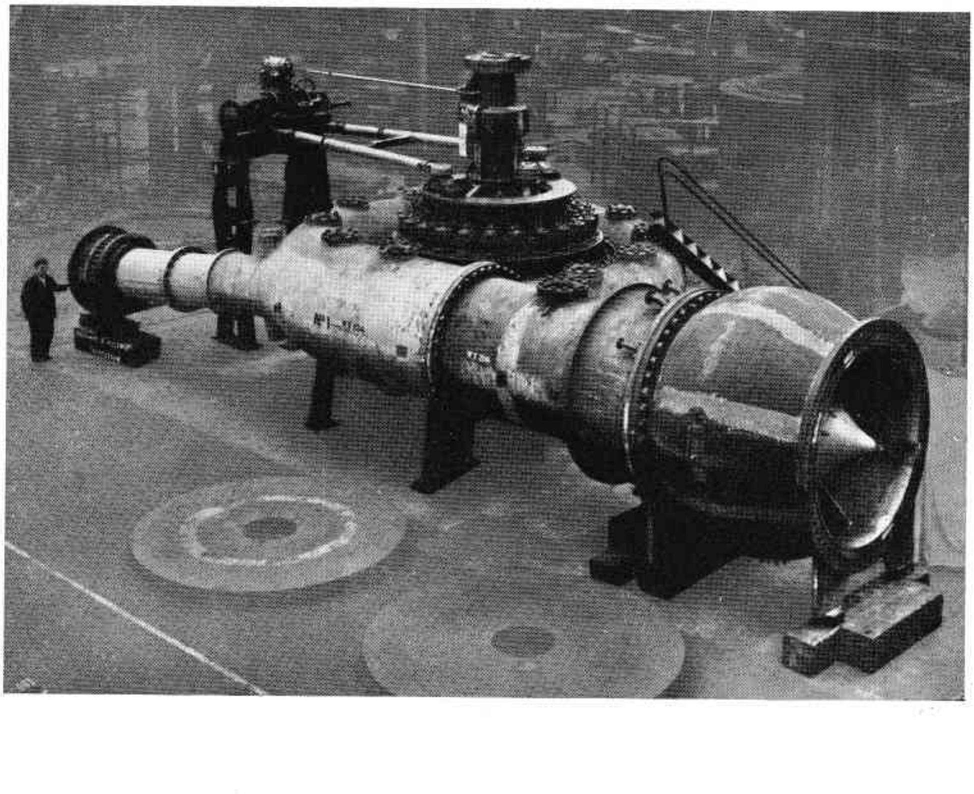
After passing through the valve the water enters the spiral casing of the vertical shaft reaction turbine. The spiral with its speed ring and stay vanes was cast in one piece and the finished weight of the casting was over 30 tons. At site the spiral is completely embedded in concrete.

A branch on the downstream side of the spiral casing is provided for connection to the relief valve which operates automatically in synchronism with the governor when load is thrown off the turbine, and so limits the pressure rise. The valve is of the same type as the turbine inlet valve.

The regulating gear is of orthodox design ; there are 24 forged steel guide vanes which control the flow of water to the runner, and these when closed cut off the supply of water to the turbine runner. The guide vanes are connected outside the spiral casing to a regulating ring through cast iron breaking links which give protection against damage if an obstruction becomes lodged between any of these vanes. The regulating ring is rotated to adjust the position of the guide vanes for load control, by substantial connecting rods operated by an oil pressure servo-motor.

In the top cover is mounted a carbon ring gland round the main shaft to prevent water passing from above the turbine runner up the shaft. The turbine shaft bearing is carried on the top cover as well as its oil sump. The bearing has forced lubrication obtained from a gear-driven pump, with a D.C. motor-driven pump as standby which is automatically controlled to cover starting up and shutting down periods when the gear pump is not delivering sufficient oil. The governor head in the actuator which controls the governor servo-motor is also gear driven from the main shaft.

Fig. 5. Assembly of turbine for Loch Sloy, with the inlet and relief valves, at the Glasgow Works of Messrs. Harland and Wolff, Ltd., subcontractors to 'English Electric'



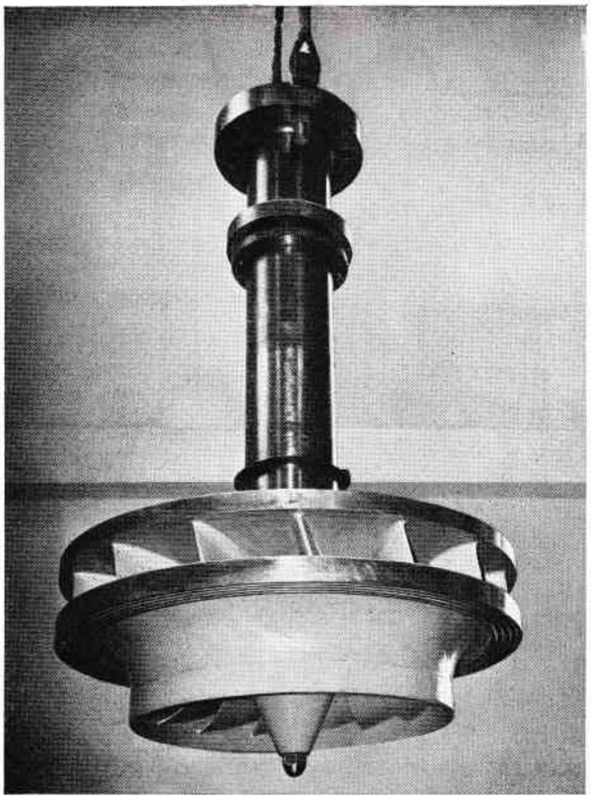


Fig. 6. *Runner and shaft for* 45,500 *h.p. water turbine*

The turbine shaft is solidly coupled to the alternator shaft above, and the torque is transmitted by transverse fitted keys which eliminate the use of fitted bolts.

The turbine runner (Fig. 6) is of interesting construction. Because of the high head the passages through the runner are very small (about 2 in. minimum) and it would have been very difficult to cast a runner with passages of sufficient accuracy or with a smooth enough finish without appreciable hand grinding. The complete runner was accordingly fabricated from steel and stainless steel plates and castings. Briefly, the method of assembling the runner was as follows :—

(i) Cast stainless steel vanes ground smooth were assembled and welded to the stainless steel crown and rim. Thus all the water passages are of stainless steel. The ingenious welding sequence developed allowed good access to every weld as it was made.

(ii) A cast steel crown disc was then welded over the crown. This disc gives great strength to the wheel and carries the torque to the shaft. At the same time a considerable weight of stainless steel is saved.

(iii) The sealing rings were shrunk on.

(iv) The complete runner was finally machined and balanced.

The sealing rings which separate the high pressure water side of the runner from the top and bottom of the runner which are at exhaust pressure, are of the multi-labyrinth type with radial clearances of approximately ·030 in. on a diameter of over 7 ft.

The design of the runner was proved by test on a $\frac{3}{10}$th scale model of the complete turbine. Accurate tests were then carried out at 'English Electric's' hydraulic laboratory at Rugby. The actual rating of the turbine is 45,500 b.h.p. at 810 ft net head and it runs at 428 r.p.m. The head range is 880 to 720 ft net.

Alternators

The 11 kV vertical direct-coupled alternators are each rated at 32,500 kW 0·95 p.f. (34,210 kVA) 428 r.p.m., and they are also suitable for generation at 27,500 kW 0·8 p.f. (34,375 kVA), although usually the power factor is nearly unity or even leading.

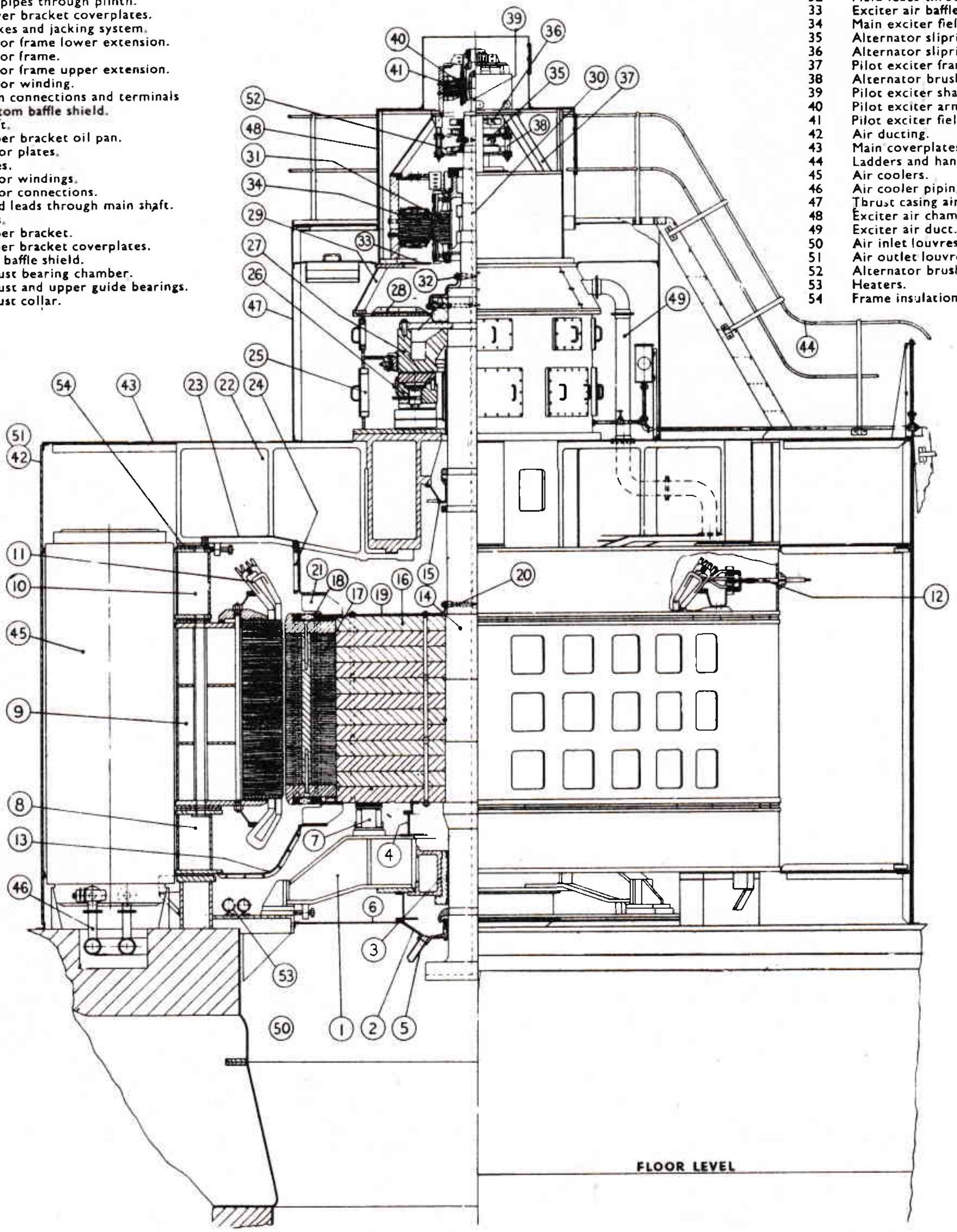
The stator, which was transported in halves, is carried on a fabricated steel support which is bolted to the turbine speed ring and encased in concrete. The winding is of the two-layer basket type of conventional design.

In common with other water turbine driven alternators, the rotor (Fig. 7) was required to be heavy to give a high flywheel effect, and had also to be designed to withstand prolonged running at the maximum runaway speed of the turbine which could occur if the turbine gates were held open with no electrical load on the machine. This speed was 793 r.p.m. and one alternator was tested under this condition in the Stafford Works. To meet these requirements, the rotor was constructed of twelve steel plates each $5\frac{1}{4}$ in. thick which were shrunk and keyed to the shaft in three packets of four plates

PLATE III **Cross-sectional view of 32,500 kW alternator with direct-coupled main and pilot exciters**

Ref. No.	Description
1	Lower bracket
2	Lower bracket oil pan.
3	Lower guide bearing.
4	Lower bracket oil baffle.
5	Oil pipes through plinth.
6	Lower bracket coverplates.
7	Brakes and jacking system.
8	Stator frame lower extension.
9	Stator frame.
10	Stator frame upper extension.
11	Stator winding.
12	Main connections and terminals
13	Bottom baffle shield.
14	Shaft.
15	Upper bracket oil pan.
16	Rotor plates.
17	Poles.
18	Rotor windings.
19	Rotor connections.
20	Field leads through main shaft.
21	Fans.
22	Upper bracket.
23	Upper bracket coverplates.
24	Top baffle shield.
25	Thrust bearing chamber.
26	Thrust and upper guide bearings.
27	Thrust collar.

Ref. No.	Description
28	Oil baffle.
29	Main exciter support.
30	Main exciter shaft.
31	Main exciter armature.
32	Field leads through exciter shaft.
33	Exciter air baffle.
34	Main exciter field.
35	Alternator sliprings.
36	Alternator slipring fan.
37	Pilot exciter frame support.
38	Alternator brushgear.
39	Pilot exciter shaft extension.
40	Pilot exciter armature.
41	Pilot exciter field.
42	Air ducting.
43	Main coverplates.
44	Ladders and handrails.
45	Air coolers.
46	Air cooler piping.
47	Thrust casing air chamber.
48	Exciter air chamber.
49	Exciter air duct.
50	Air inlet louvres and filters.
51	Air outlet louvres.
52	Alternator brush.
53	Heaters.
54	Frame insulation.



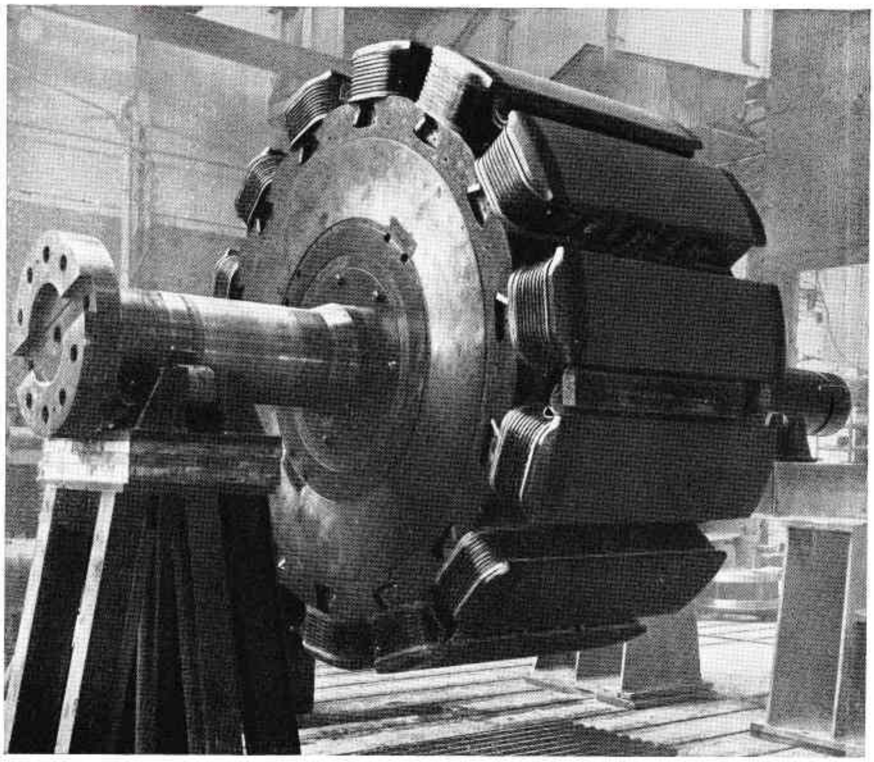


Fig. 7.
Rotor for 32,500 *kW* 428 *r.p.m. vertical shaft alternator*

each. The poles, which are built up from laminations with thick cast steel end plates, are fixed to the rotor in dovetail slots and held by taper side keys. The complete rotor weighs 107 tons.

The alternator is of the two-bracket type in which the thrust bearing for carrying the rotor is located above the stator, and there is a guide bearing on each side of the rotor. The upper guide is combined with the thrust bearing in a common chamber and both are of the pivoted pad type. The thrust bearing supports the weight of the rotor and also the hydraulic thrust from the turbine runner, amounting to a total of 235 tons. This load is transferred to the foundations through the stator frame and generator support. The oil supply to the bearings is obtained from electrically driven " Imo " pumps, and the thrust bearing is so arranged that if the oil supply fails, sufficient oil is retained in the bearing by means of an outlet weir to enable the set to be brought to rest without damage to the bearing.

The normal oil supply is from an A.C. motor-driven pump, with a D.C. motor-driven pump as an automatic standby controlled by a flow relay in the delivery branch from the main pump. The oil is cooled by water circulation in a single vertical cooler. This lubrication system is completely separate from the one already described for the turbine bearing.

The lower guide bearing is of the sleeve type, split into halves for dismantling, and its oil supply is from the same system as for the upper bearing. The lower guide bearing is carried in the lower bracket below the stator, and this bracket also carries the brakes which are Ferodo lined and bear on the under surface of the rotor when shutting down. The use of these brakes avoids prolonged running at slow speeds which is detrimental to the thrust pads. Compressed air for the brakes at a pressure of 55 lb/sq. in. is obtained through a solenoid operated valve and reducing valve from a standard ' English Electric ' type AC2 compressor which is common to all four sets. The compressor equipment also delivers air at 300 lb/sq. in. for occasional charging of the governor receivers. The brakes can also be supplied with oil at 2,000 lb/sq. in. from a hand-operated pump to lift the rotor when inspection or replacement of the thrust pads is required.

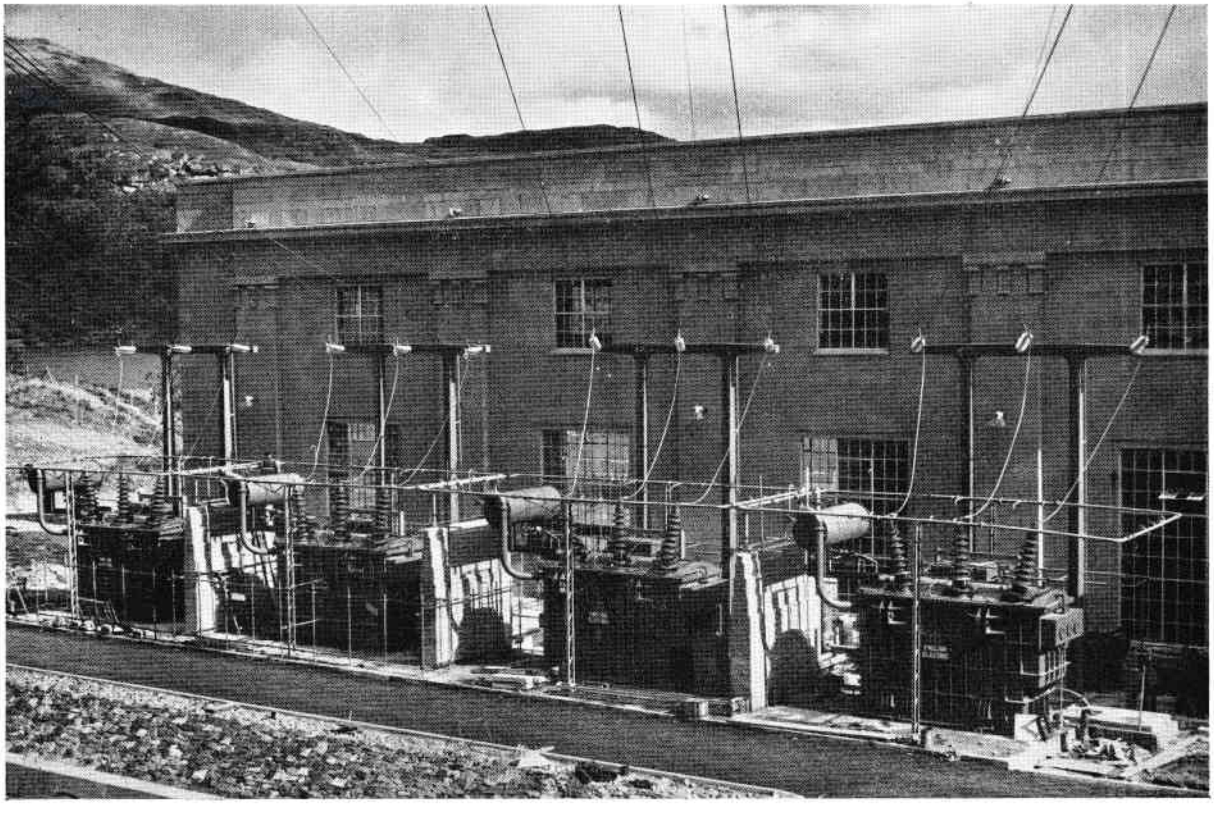
The main and pilot exciters are directly coupled to the upper end of the alternator shaft. The pilot exciter is self-excited and supplies the field of the main exciter at a constant voltage, the current to the field being controlled by an automatic voltage regulator. The output of the main exciter is connected through a main field circuit-breaker to the alternator rotor. The sliprings are located above the main exciter and the connections to the rotor are taken down the centre of the shaft.

The alternator and exciters are totally enclosed, air being circulated by fans fitted to each side of the rotor. Six vertical coolers are located round the stator. Part of the air is diverted to the exciters and this air returns through a filter to ensure that no carbon dust is carried from the brushes to the alternator.

In addition, some air can be diverted into the turbine room through louvres in the top of the stator air ducting. Make-up air enters the alternator through further louvres in the plinth and passes through filters.

A CO_2 fire extinguishing equipment is common to all four sets and is operated by electrical push buttons which release two sets of cylinders to the appropriate alternator through two sets of nozzles placed near the top and bottom fans. The first set of nozzles is arranged to give a quick discharge so that a heavy concentration may be built up rapidly, and the second set admits gas gradually to ensure that the concentration is maintained for a sufficient time to allow the machine to shut down and the fire to be extinguished. The cylinders are located in a pit below floor level in the turbine room. When CO_2 is released to any machine, pressure-operated devices automatically close the louvre doors to prevent escape of the gas.

Fig. 8. *The four* 35,000 *kVA* 11/132 *kV generator transformers*



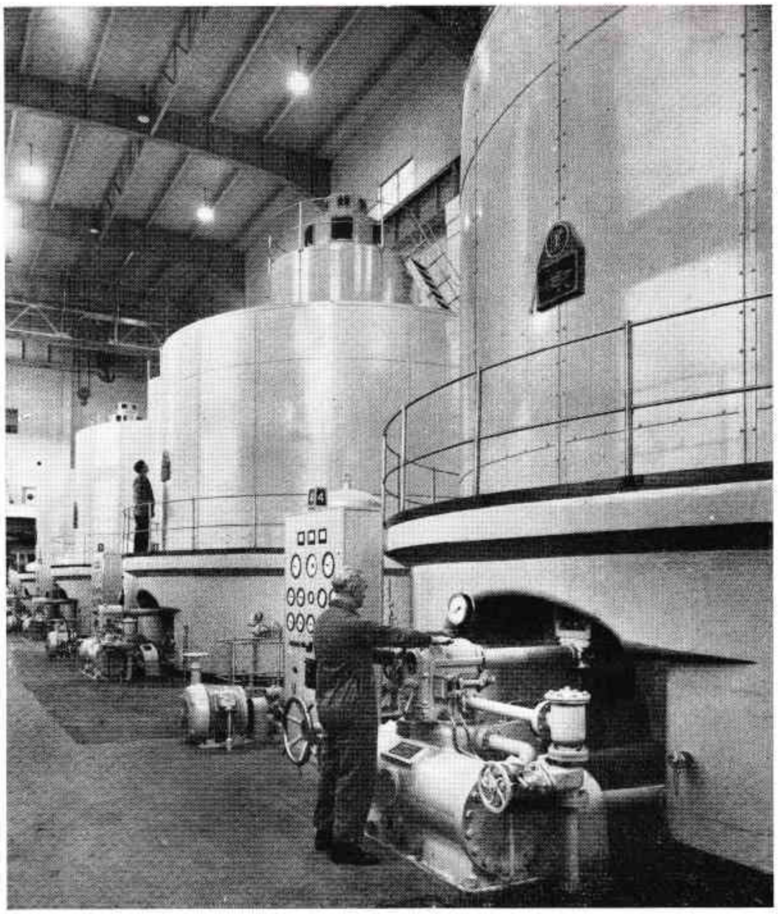


Fig. 9. Downstream side of generating sets, showing turbine governor and instrument panel

The water supply for the air and oil coolers is obtained from motor driven pumps. The pumps for the four sets, with an additional standby pump of double the size, are grouped together in a pit below normal tail water level in an annex to the power station.

Transformers

Each alternator is connected solidly to a step-up transformer through two 1 sq. in. single core cables in parallel per phase, and the power from each transformer is transmitted by a 132 kV overhead line to the switching station at Inveruglas, about one mile from the power station. The transformers, shown in Fig. 8, are 3-phase units each rated at 35,000 kVA, and step-up from 11 to 132 kV. Cooling is by forced oil circulation with duplicate water coolers and oil pumps which are located in two chambers between the transformers, each chamber containing the cooling equipment for two transformers. The cooling water supply is taken from the system supplying the alternators and turbines.

The high voltage winding is provided with tappings to give from 0 to +15 per cent. in 10 steps for the addition, at a future date, of on-load tap changing gear.

Mulsifyre fire protection is provided for the transformers, and this also covers the cable galleries in the power station.

Control

The turbines and alternators are manually controlled, starting and stopping of a turbine being effected by the levers situated on the top of the actuator.

Most of the gauges and indications for a turbine and alternator are grouped on the instrument panel at the left-hand side of the governor, as seen in Fig. 9. The equipment on each panel includes a flashing alarm beacon with three 6-way alarm facias giving indication of the following conditions :—

Condition	Initiating device
Governor oil pump failure	Flow relay.
Governor oil pressure low	Pressure relay.
Alternator lubricating oil flow failure . .	Flow relay, time delayed.
Thrust bearing low oil level	Level switch.
Low air pressure (on one set only) . .	Pressure relay.
Thrust bearing temperature high . .	Thermometer.
Upper guide bearing temperature high	Thermometer.
Lower guide bearing temperature high	Thermometer.
Turbine guide bearing temperature high	Thermometer.
Thrust bearing oil outlet temperature high	Thermometer.
CO_2 released	Auxiliary contact on release solenoid.
Faulty air brakes valve	Pressure relay.
Main valve trip on fault	Tripping relay.
Air inlet temperature high	Thermometer.
Air outlet temperature high	Thermometer.

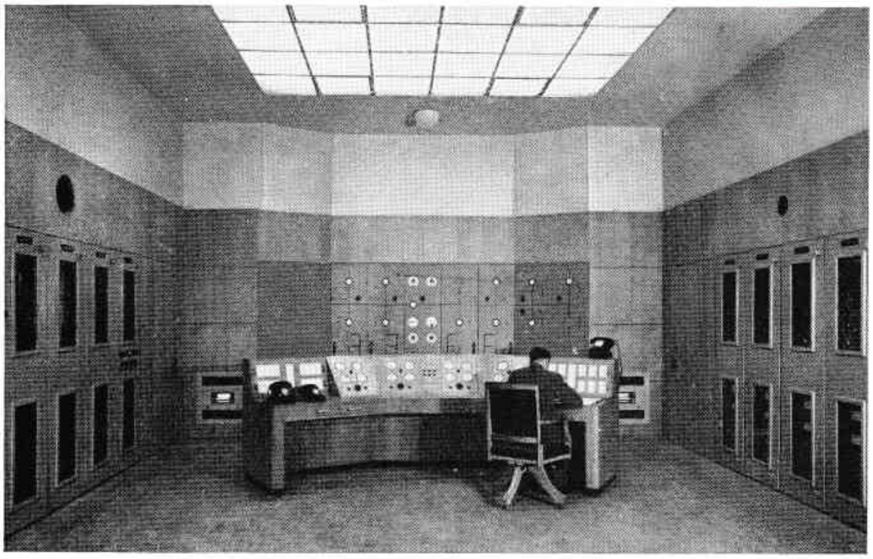


Fig. 10. The control room

The equipment of each panel also includes :—

Pipeline water pressure gauge.
Spiral casing water pressure gauge.
Alternator indicating wattmeter.
Thermometers corresponding to the alarm indications listed above.
Running-hours recording meter.
Draught tube vacuum gauge.

Indicating lamps for :—

- **Alternator standby lubricating oil pump running.**
- **Turbine standby lubricating oil pump running.**
- **Air brakes on.**
- **Turbine inlet valve open or closed.**
- **Governor oil flowing.**

Control switches or push buttons for :—

- Alternator brakes.
- Emergency trip.
- CO_2 release.
- Alarm acceptance.
- Alarm lamp test.

Protection is provided to ensure the automatic shut-down of a set under any of the following conditions :—

Thrust bearing oil flow failure.
Governor drive failure.
Governor oil pressure low.
Overspeed.
Over-voltage.
Bus-zone fault.
Electrical fault on alternator, transformer or transmission line (by Translay protection).
Main transformer fault (by Buchholz relay).
Main transformer winding temperature high.
Unit transformer fault (by Buchholz relay).

Control of the auxiliary motors is not carried out from the instrument panel but by push buttons located on the starters which are grouped in a unit board on the upstream side of the set.

When a generating set is running, synchronising and load control is carried out from the control room, shown in Fig. 10. This contains a control desk for the generating sets, a control board with mimic diagram and synchronising instruments, the automatic voltage regulators (left) and the relays and temperature indicating instruments (right).

The main control of the switchgear and the sets is effected by telephone-type equipment, operating on 50 volts with light currents, and therefore telephone-type cables (20 lb per mile, 1/·036 in) are used. The load, speed, voltage and power factor of each machine are controlled from the desk, where indications are given of the load, power factor, rotor current and rotor voltage. The control and position indication for the generator circuit-breakers are also located on the desk together with alarm facias, of the same type as those used on the turbine instrument panels, to give indication of the following fault conditions.

Each generating set :—

Governor oil pressure failure.
Governor drive failure.

Generator bearing lubricating oil flow failure.
Mechanical failure.
Overspeed.
External fault.
Over-voltage.
Winding temperature high.
Generator earth fault.
Breaker tripped.
Automatic voltage regulator cut out.
Internal fault.
Cooler water failure.
Transformer oil pump failure.
Main transformer Buchholz gas.
Unit transformer Buchholz gas.
Low air pressure.

Each feeder circuit :—

Primary protection operated.
Back-up protection operated.
Breaker tripped.
Low air pressure in circuit-breaker local receiver.
Protection out (except Shira feeder).
Valve failure in carrier current equipment (except Shira feeder).

Bus-section and bus-zone circuits :—

Breaker tripped.
Primary protection operated.
Low air pressure in circuit-breaker local receiver.
Tripping relay operated.
Protection unstable, zone 1.
Protection unstable, zone 2.
Protection out, zone 1.
Protection out, zone 2.
Bus-zone tripped, zone 1.
Bus-zone tripped, zone 2.

Miscellaneous circuits :—

Fuse alarms.
Pilot alarm.
Battery charger failure.
Telemetering fuse alarm.
Trip supply failure.
Fire protection operated.
Carrier current equipment power unit fault.
Carrier current equipment power unit failure.
Main receiver low air pressure.

Control of the feeder and bus-section circuit-breakers is carried out from the control board, the mimic diagram on which shows the main electrical circuits and also the turbines and alternators.

The method of circuit-breaker control is novel. If it is desired to close a breaker, the appropriate control selector switch is rotated which automatically connects the synchronising instruments to the circuit concerned. Synchronising is then carried out manually, and when synchronism is reached the breaker is closed by pressing a small push button in the centre of the control switch. To trip the breaker the same push button that is used for closing is pressed without first operating the selector switch.

The automatic voltage regulators for the alternators are behind glass doors on the left-hand side of the control room, and the relays, with the alternator and transformer temperature indicating instruments, are on the right-hand side. The

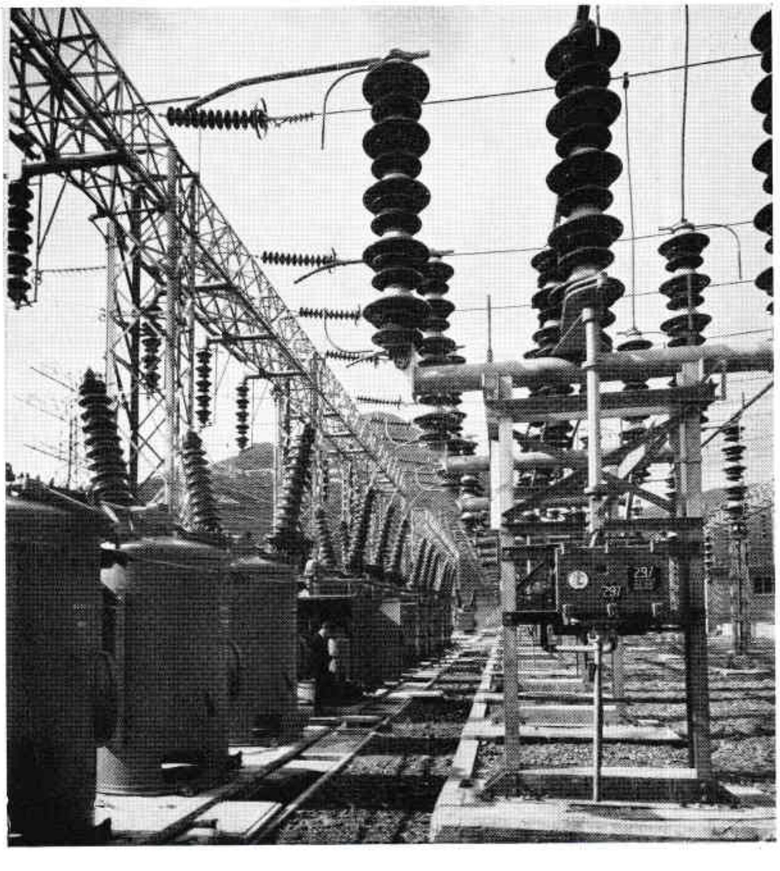


Fig. 11. *Part of the* 132 *kV switching station at Inveruglas, during construction* purpose of the glass doors was to give a flush appearance to the control room although using projecting-type instruments and relays.

A local telephone exchange is included in the control desk which is also served by a G.P.O. line. There is also direct telephone connection with Tummel control centre, and Windy Hill switching station of the British Electricity Authority about 25 miles distant, over the 132 kV transmission lines by carrier current equipment.

Auxiliary Switchgear

In a hydro-electric station the auxiliary switchgear is very simple, particularly when a unit system is adopted, as can be seen from the key diagram. The motor-starter boards are normally supplied from a unit transformer but an alternative supply is available from the common services board. This board is supplied by an auxiliary impulse-type water turbine driving a 450 kW 415 volt alternator, and also at present from the temporary diesel engine station built for the construction work of the scheme. The common services board is composed of 'OB3' air-break draw-out type circuit-breaker units and 'Combination' fuse-switches. The lighting and heating boards are also of the 'Combination' fuse-switch type.

D.C. supplies for the control of the generating sets and emergency services are obtained from a 50 volt 100 ampere-hour battery and a 110 volt 300 ampere-hour battery, and are distributed through a live-front D.C. board in which the constant-voltage battery chargers are also included.

Transmission Lines and Switching Station

As previously mentioned, the high-voltage terminals of the step-up transformers are solidly connected to two double-circuit 132 kV transmission lines, each approximately one mile long, to the switching station at Inveruglas.

The switching station, of which a section during construction is shown in Fig. 11, is of the single busbar type. There are four generator circuits, initially six feeders, and one bus-section. Three of the feeders are to Glasgow, one to a neighbouring hydro-electric scheme at Shira, for which 'English Electric' is also supplying most of the plant, and two connect with the 132 kV system of the North of Scotland Hydro-Electric Board in north-east Scotland. Space is included for a total of 16 circuits and the bus-section.

The structures for supporting the busbars and isolating switches are of steelwork. The circuit-breakers are of the bulk-oil dead-tank type and have arc control devices of the latest design which enabled the internal diameter of the tanks to be reduced from 62 in. to 54 in. with a corresponding reduction in the oil content from 1,000 to 600 gallons per phase. The breakers are rated at 1,500 MVA and are provided with high-speed pneumatic closing mechanisms. They are, as already stated, normally controlled from the power station by means of direct pilot wires, but provision is made for local electrical control at the circuit-breaker.

The isolators are of the usual rotating centre pillar type, hand operated but with remote indication of position.

The compressors, which provide air at 150 lb per square inch for operating the breakers, are housed in a plant house which also contains the local relay board, a 110 volt 150 ampere-hour battery and a battery board.

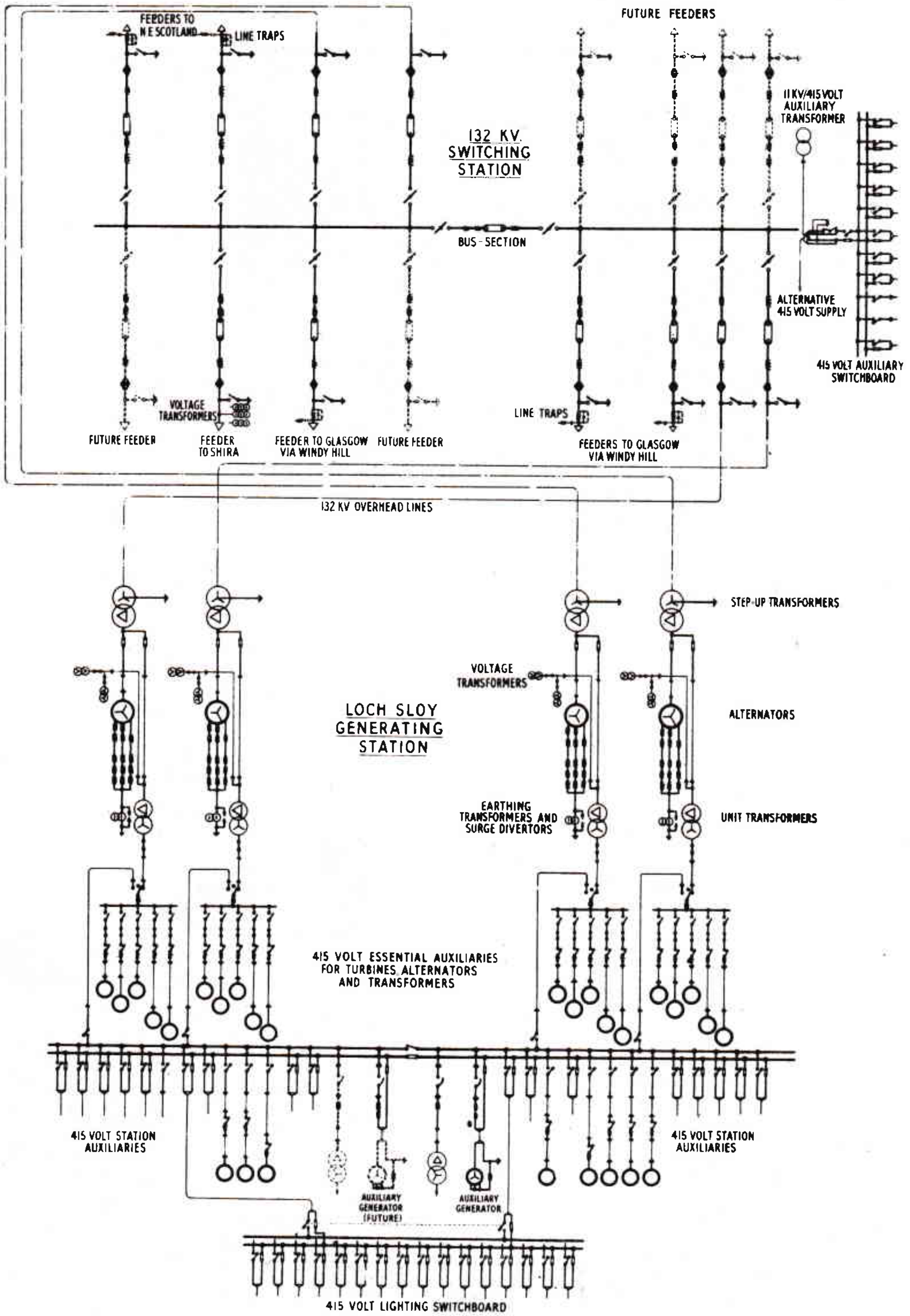
Protection

Protection of the feeders, except the Shira feeder, is by telephone equipment using carrier currents, with back-up overload protection. Line traps are provided which block the high frequency carrier signals so that they are not fed into the busbars, and the signals are led to the carrier current equipment by means of co-axial cables. The Shira feeder, which is a two-way feed, is protected by ratio balanced protection energised from a 132 kV wound voltage-transformer.

Protection of the interconnectors to the power station is by overall Translay which covers the zone from the generator neutrals to the busbar side of the generator breakers including the generator windings, cable, transformer, transmission line and breaker. Negative phase sequence protection is also included for the generator.

The busbars are protected by bus-zone protection divided into two sections which correspond with the sectioning of the busbars by the bus-section switch which is included in both sections to give overlapping.

PLATE IV **Key diagram of main and auxiliary electrical system**


FEEDERS TO N E SCOTLAND
LINE TRAPS
FUTURE FEEDERS
132 KV. SWITCHING STATION
11 KV/415 VOLT AUXILIARY TRANSFORMER
BUS - SECTION
ALTERNATIVE 415 VOLT SUPPLY
415 VOLT AUXILIARY SWITCHBOARD
VOLTAGE TRANSFORMERS
LINE TRAPS
FUTURE FEEDER
FEEDER TO SHIRA
FEEDER TO GLASGOW VIA WINDY HILL
FUTURE FEEDER
FEEDERS TO GLASGOW VIA WINDY HILL
132 KV OVERHEAD LINES
STEP-UP TRANSFORMERS
VOLTAGE TRANSFORMERS
LOCH SLOY GENERATING STATION
ALTERNATORS
EARTHING TRANSFORMERS AND SURGE DIVERTORS
UNIT TRANSFORMERS
415 VOLT ESSENTIAL AUXILIARIES FOR TURBINES, ALTERNATORS AND TRANSFORMERS
415 VOLT STATION AUXILIARIES
AUXILIARY GENERATOR (FUTURE)
AUXILIARY GENERATOR
415 VOLT STATION AUXILIARIES
415 VOLT LIGHTING SWITCHBOARD

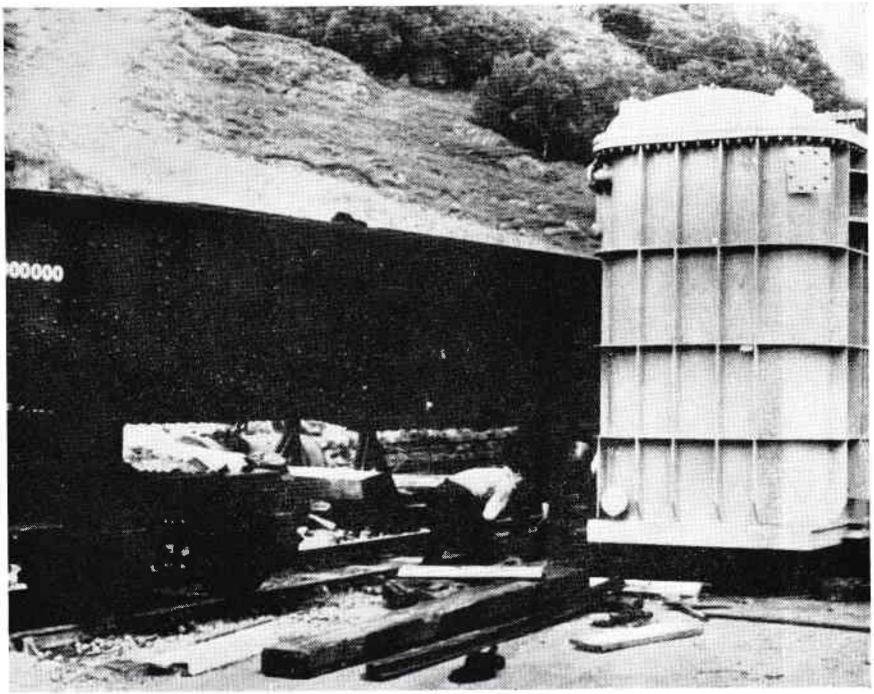


Fig. 12.
A generator transformer weighing 71 tons being off-loaded at Inveruglas

Transport

A project the size of Loch Sloy involves not only the design, drawing and manufacture of the mechanical and electrical equipment but also the problem of delivery to site and erection.

The first parts to be delivered were the draught tubes which although not heavy were rather bulky, as they were delivered in one piece to avoid site welding. Each spiral casing with its foundation ring weighed 42 tons and although its weight was not excessive, it was the heaviest part to be transported by road all the way, and the width was considerably beyond the normal transport limits.

The alternator rotors with poles removed weighed $84\frac{1}{2}$ tons each and were transported by rail to a special siding built for constructional purposes at Inveruglas. There was no crane of sufficient capacity at the siding for off-loading, and the transfer to the road vehicle for transport to the power station was carried out by jacking.

The transformers each weighing 71 tons were transported in a similar way, but a special transformer rail-waggon was used. Fig. 12 shows a transformer being off-loaded at the siding.

The alternator stators were despatched in halves, each weighing $33\frac{1}{2}$ tons, and like the spiral casings they were transported by road throughout.

Erection

The first parts to be erected were the draught tubes which had to be positioned before any of the power station steelwork was built, and a temporary crane was used. The photograph reproduced in Fig. 13 was taken late in 1947 when the third draught tube was being placed in position. This illustration shows part of the concrete portion of the draught tube and the concrete foundations for the power station steelwork ; the ground is being cleared for the pipelines, and the railway bridge for passing over them is already finished.

Generally, after placing the draught tubes in position very little erection work can be done on the plant until the power station crane is operating and protection from the weather is built. At Loch Sloy, however, the civil progress was such that erection of the turbines had to proceed before the walls were completed, and with the prevailing weather the working conditions were at times not good. Fig 14 shows the state of erection in the spring of 1949 when three of the turbine spiral casings were in position. The inlet pipe and relief valve branch are also erected on the set at the far end of the station. The concrete walls are being built from scaffolding on the inside and the outside of the station.

It is worth recalling that when the first generating set was completed, Sir Edward MacColl of the North of Scotland Hydro-Electric Board set it in motion for the first time, without any previous trial run, at 3.15 p.m. on the 18th February 1950. The set was then taken up to full speed and ran entirely satisfactorily. This was a great tribute to all who had worked on the design, manufacture, and particularly erection, overcoming many difficulties. The first set was put into commercial service on 6th March 1950, and the remaining three sets on the following dates :—

2nd set	20th July 1950.
3rd set	30th November 1950.
4th set	1st February 1951.

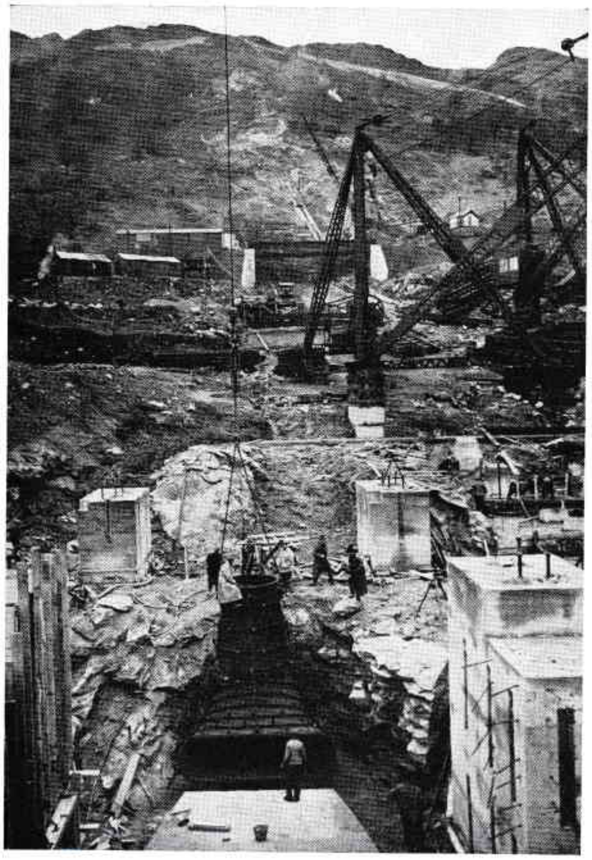


Fig. 13. *Placing the third draught tube in position*

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The consulting engineers were :—Messrs. James Williamson and Partners, for the civil engineering. Messrs. Kennedy and Donkin, for the mechanical and electrical power station plant. Messrs. Merz and McLellan, for the switching station.

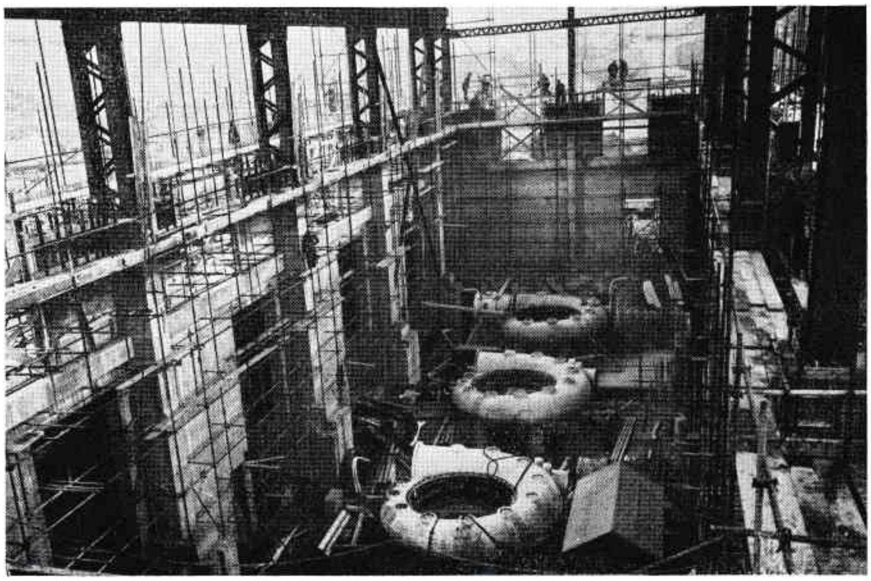

Fig. 14.
Three spiral casings in position during erection

Performance Tests on the Turbines and Alternators

Turbine Field Tests

The efficiency tests for the turbines were carried out on the second machine at site and took place after it had been in service for a year.

The set was run on commercial load, the output and power factor being kept as constant as possible by generating in parallel with another of the sets which could take any load swings. The electrical output was measured by special instruments and instrument-transformers calibrated with the interconnecting leads at the National Physical laboratory.

The rate of flow to the turbine and the pressure at the entrance of the spiral casing were both measured by the British Pitometer Company, Limited, using, for the first, the Allen Salt Velocity Method in the pipe line from the brine injection station at the top down to the electrode station just above the lowest anchor block shown in Fig. 4 ; and, for the second, a direct-reading manometer at the valve house, connected to a pipe line without flow, and a differential manometer at the power house, connected on one side to the same static pipe line and on the other to the spiral casing of the machine on test.

The high water level maintained at the dam did not allow the tests to be run at the design net head of 810 ft., at which the weighted overall efficiency of the sets was guaranteed.

Fig. 15 is the graph of turbine efficiency against output at the gross head of 898-899 ft., the net heads ranging from 883·0 ft. to 891·4 ft. The relation between turbine and model tests gives a maximum efficiency of 92·0 per cent. for the turbine at the net head of 810 ft. and a weighted overall efficiency of the set in excess of guarantee by 1·5 per cent.

Fig. 16 is an example of a tachogram taken in the governor trials before the set went into service. This shows the rise of speed on rejection of 97 per cent. of full load (31,500 kW), and the smooth return to steady speed that is a feature of these governors.

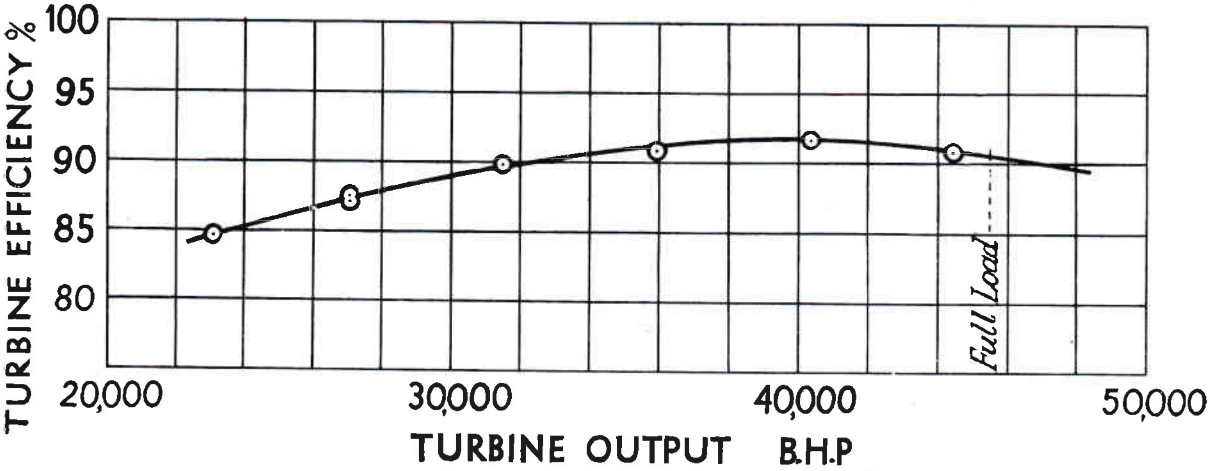

Fig. 15. Results of field tests at 898-899 ft. gross head.

Alternator Factory Tests

As already stated, one of the alternators was run in the Stafford Works. Tests were carried out to determine open-circuit and short-circuit characteristics and losses, the latter being obtained by the retardation method. The efficiencies calculated from these tests are shown in Fig. 17. A three-phase instantaneous short-circuit was applied to the terminals when the alternator was generating rated volts on open circuit, and an oscillogram record taken of the currents in the three-phase windings in order that the transient and sub-transient reactances could be determined.

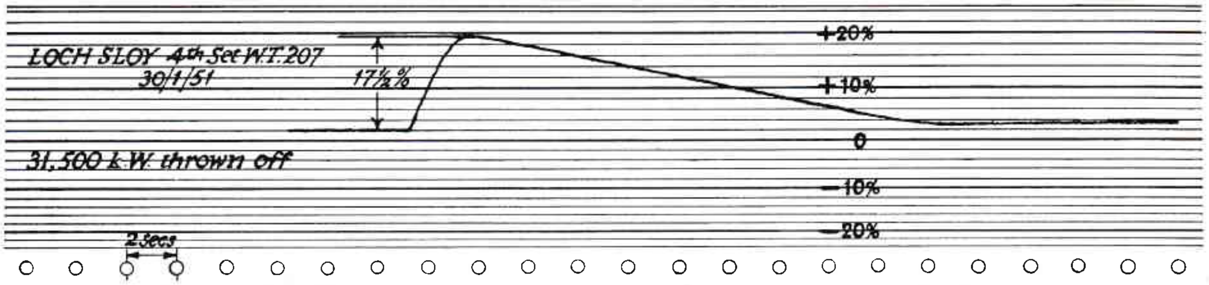

Fig. 16. Example of tachograms taken on rejection of load.

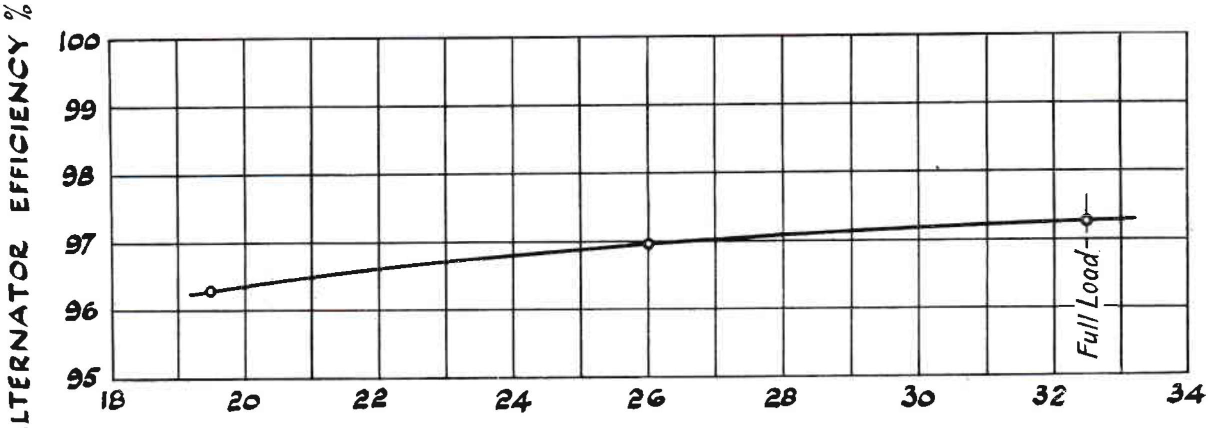

Fig. 17. Alternator efficiency at 0·95 P.F.

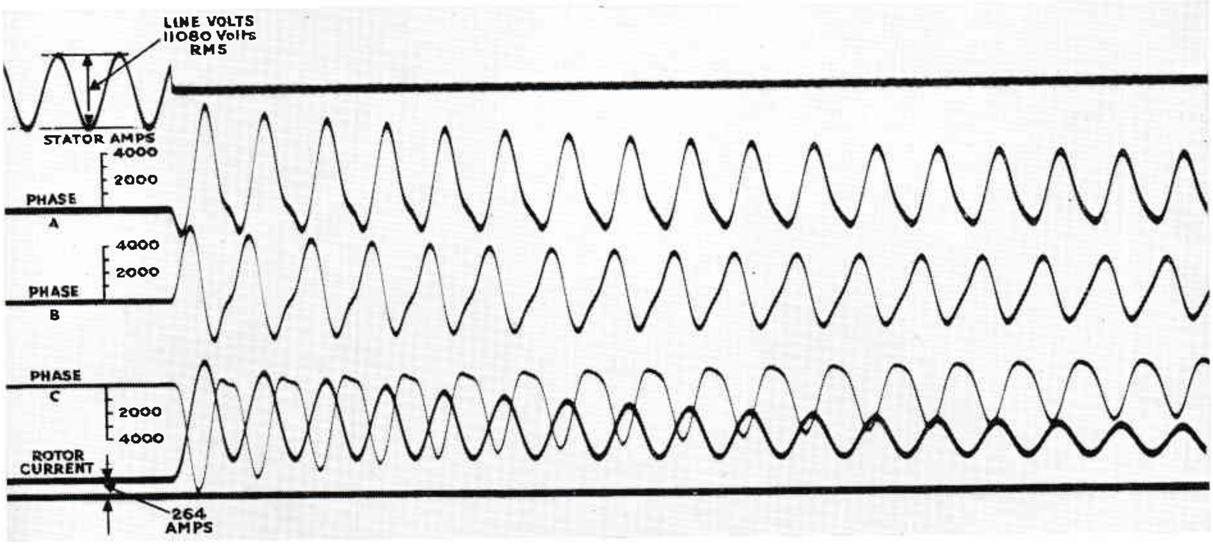

Fig. 18. 3-phase short-circuit at full volts on vertical alternator for Loch Sloy.